Apophis Specific Action Team

Jessie Dotson, Marina Brozovic, Steven Chesley, Stephanie Jarmak, Nicholas Moskovitz, Andrew Rivkin, Paul Sanchez, Damya Souami, Timothy Titus

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Report available at https://www.lpi.usra.edu/sbag/documents/Apophis_SAT.pdf

Rationale

Asteroid (99942) Apophis's Earth close approach on April 13, 2029 will be an extremely rare event. Passages of an object this large or larger, this deep or deeper through Earth's gravitational tidal field, are estimated to occur at a mean interval on the order of a thousand years. In principle, the effects of such a tidal encounter on a small body may provide a window into physical properties that would otherwise be inaccessible, Jupiter's 1992 tidal shredding of comet Shoemaker-Levy 9 being a vivid example. However, in terms of the differential tidal stress across the body, the Apophis encounter with Earth will be roughly three orders of magnitude weaker, and the detectable consequences are ambiguous. Thus, it is not fully understood to what extent this rare event offers comparably rare – and realizable – science opportunities.

Some such opportunities may be realizable using Earth-based telescopes; others may require a spacecraft in the close vicinity of Apophis. Given this possibility, the fact that Apophis is a potentially hazardous object cannot be overlooked. It has been definitively determined that Apophis will not hit the Earth in 2029, and that it will not pass through any of the keyholes that would lead to an Earth impact later this century. However, while it seems unlikely that an interaction between a spacecraft and the asteroid, intentional or accidental, could move Apophis into a keyhole or otherwise increase the risk of a future Earth impact, such a scenario has not yet been decisively ruled out for all possible mission profiles.

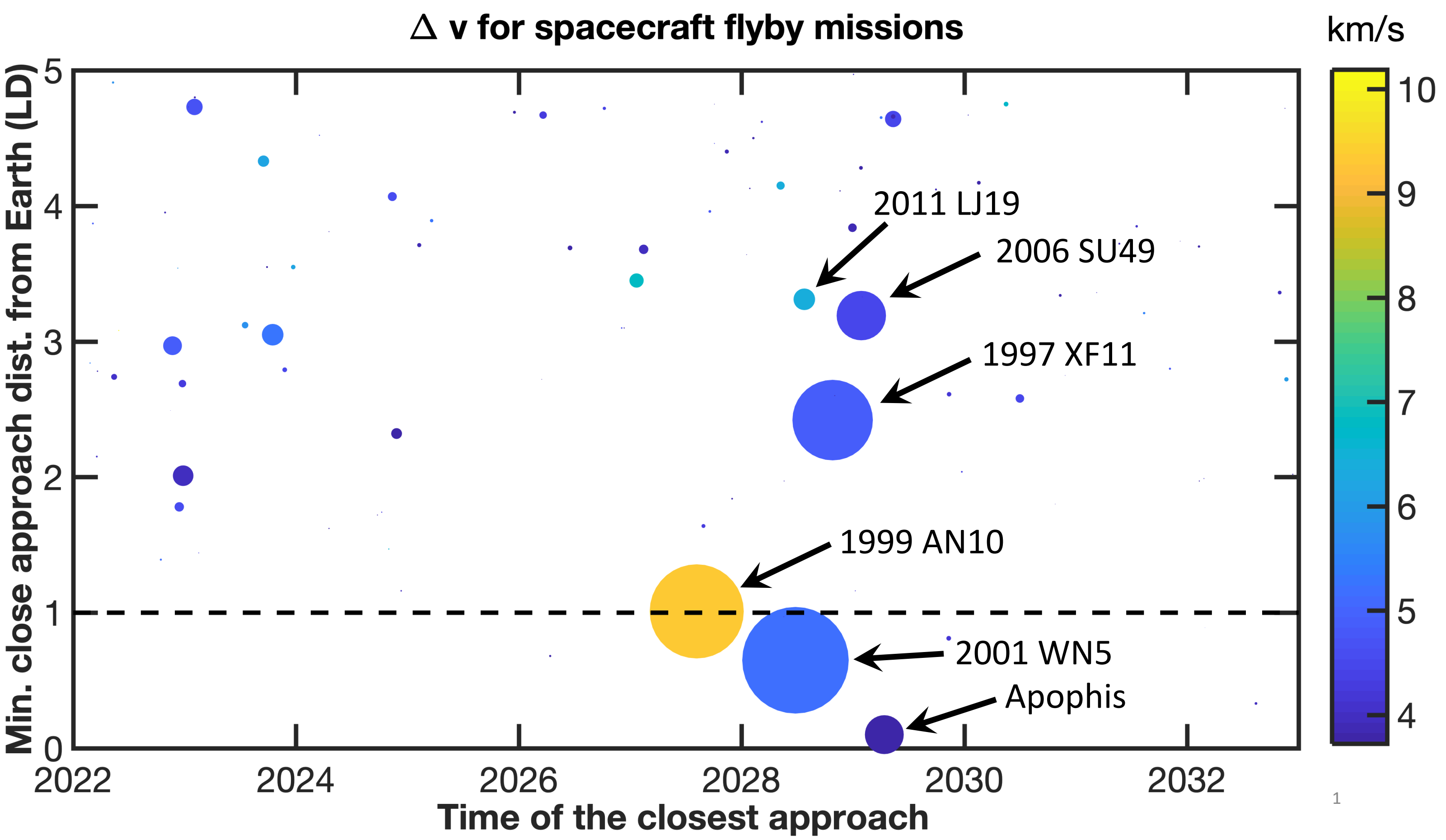
Statement of Task

1. Identify and quantify the detectable effects on Apophis expected to result from the Earth encounter and identify the measurements and instrumental sensitivities needed to detect them and determine their magnitudes.
2. Assess and prioritize the importance to planetary science and planetary defense of detecting and measuring each of these effects, as well as the value of non-detections (upper limits).
3. Categorize these effects according to
    a) detectable using Earth-based assets,
    b) detectable using a spacecraft arriving only after Earth close approach,
    c) detectable using a spacecraft arriving before Earth close approach
4. Quantitatively assess the possibility that spacecraft sent to Apophis could increase the risk of a future Earth impact.

The study shall not:

1. Assess, prioritize, or recommend specific instruments, facilities, flight hardware, mission profiles, or concepts
2. Consider observations or measurements that are not specific to the physical effects of the Earth encounter unless ~~communication~~ advantages afforded by the close proximity to Earth would enable unique measurements that would otherwise be impossible.

The Apophis close approach is a rare event



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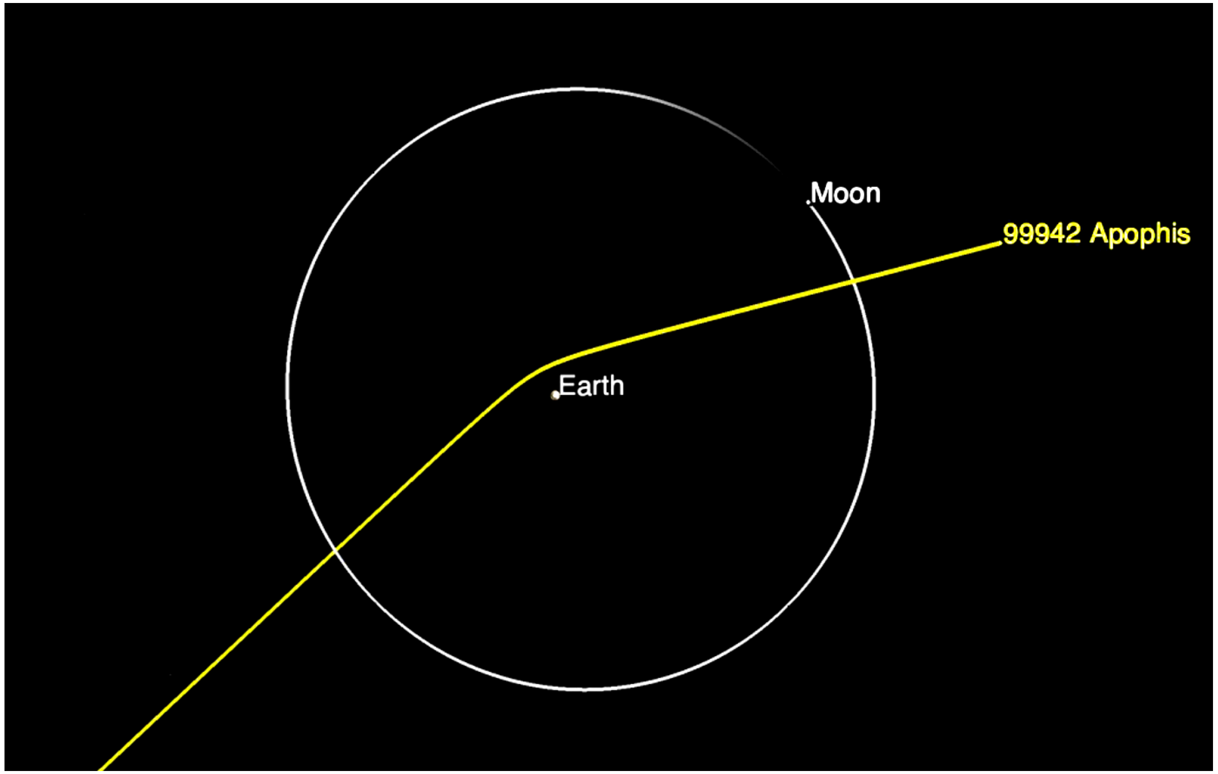
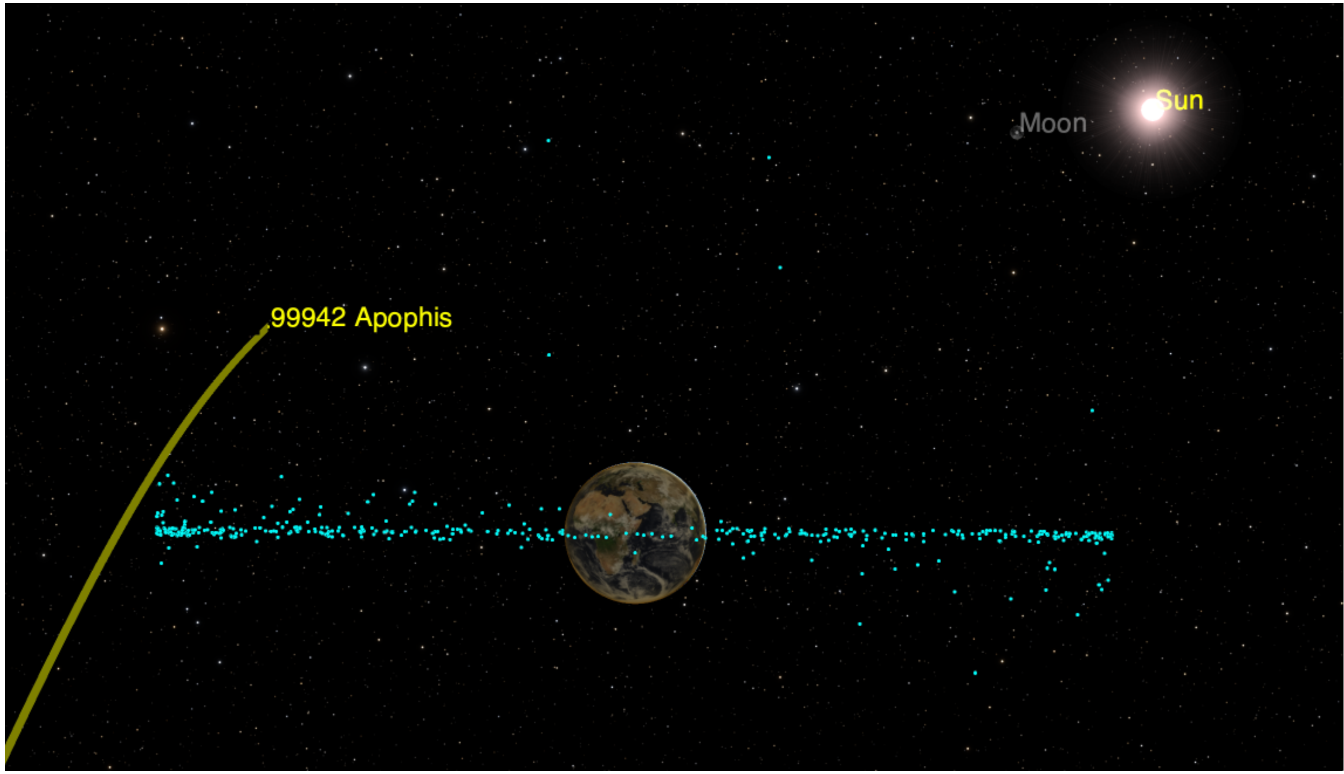
Close Approach Geometry

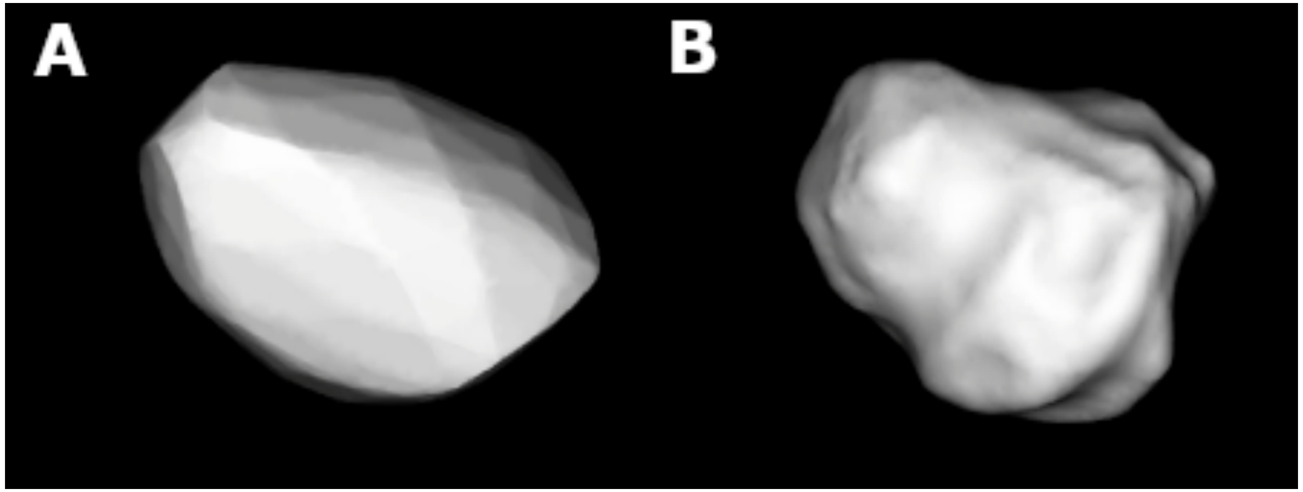




Apophis approaches from below the ecliptic plane on the night side. The closest distance will be ~ 38,000 km at 21:46 UT on April 13, 2029. The asteroid gets closer than geosynchronous satellites, though it does not pass through the belt.

Current knowledge about Apophis

- Sq class asteroid with a spectrum closely resembling LL ordinary chondrite meteorites
- Equivalent diameter from radar = 340 $\pm$ 40m (Brozkovic et al 2018)
- Shape is elongated, and possibly bifurcated (Pravec et al 2014; Brozovic et al 2018)
- Non-Principal-Axis rotator with a slow apparent rotation period of ~ 30.6 hours.
    - P_phi = 27.38 $\pm$ 0.07 hours; P_psi = 263 $\pm$ 6 hours (Pravec et al 2014)
    - P_phi = 27.3855 $\pm$ 0.0003 hours; P_psi = 264.18 $\pm$ 0.03 hours (Lee et al 2022)



Effects of the 2029 Earth Encounter on Apophis

- Quantitative predictions of available models vary due to
  - Different modeling approaches – rigid body, self-gravitating granular aggregate, finite element modeling, soft sphere discrete element model, …
  - Different assumptions for unknown properties – density, strength, internal structure…
  - Uncertainties in available measurements – shape, rotation, orientation at encounter,…
- Publications use the measurements available, but more precise measurements may have subsequently become available (e.g. radar shape model, Lee et al 2022 rotation state)
- Not all plausible configurations have been modeled (e.g. contact binary)
- Not all plausible effects have been modeled (e.g. electrostatic lofting)

→ *Available literature does not enable a definitive quantification of the likely effects of the encounter*

Qualitative Assessment of the Effects of the 2029 Earth Encounter on Apophis

most likely

- Apophis' orbit **will** change from an Aten to an Apollo orbit
- Apophis' spin state **will most likely** change significantly
- Apophis **may** experience localized areas of resurfacing
- Apophis **might** experience small changes in shape

least likely

Observational Capabilities

- A wide variety of observational capabilities will have rare opportunities during the close encounter – either due to prospect of observing the effects of the encounter or due to the nearness / brightness of Apophis

- The SAT investigated a variety of remote observing techniques including
  - photometry, spectroscopy, polarimetry, and imaging at wavelengths varying from optical through submillimeter
  - Radar frequencies in the GHz and MHz range
- The SAT investigated a variety of in situ observing techniques including
  - Multi-band high resolution optical/near-ir imaging
  - Seismometry

- *The SAT does not endorse any particular facility, instrument, or mission – but does mention specific facilities and instruments in order to illustrate relevant capabilities*

Criteria for Prioritizing Investigations

- Investigation must capitalize on the close encounter
- Result of investigation must provide valuable information for Planetary Science and/or Planetary Defense
- Investigation must rely on mature, demonstrated technologies

Top Priority Investigations

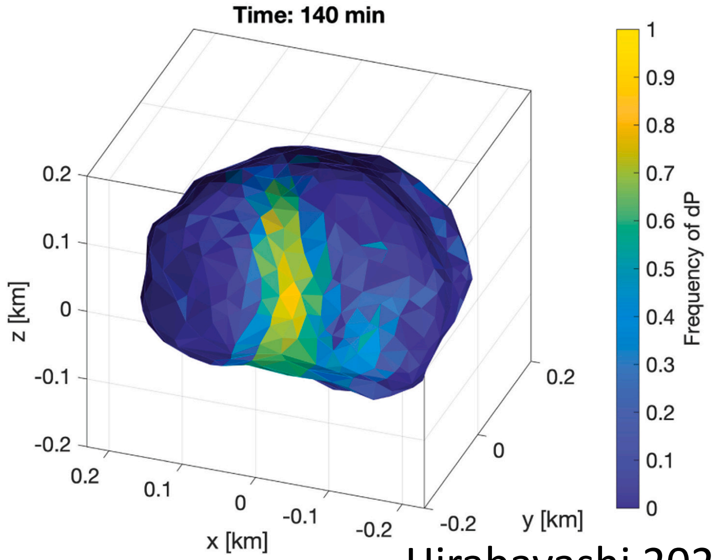
- Direct observations of resurfacing due to tidal effects

- Leverage spin change to investigate mass distribution and interior strength

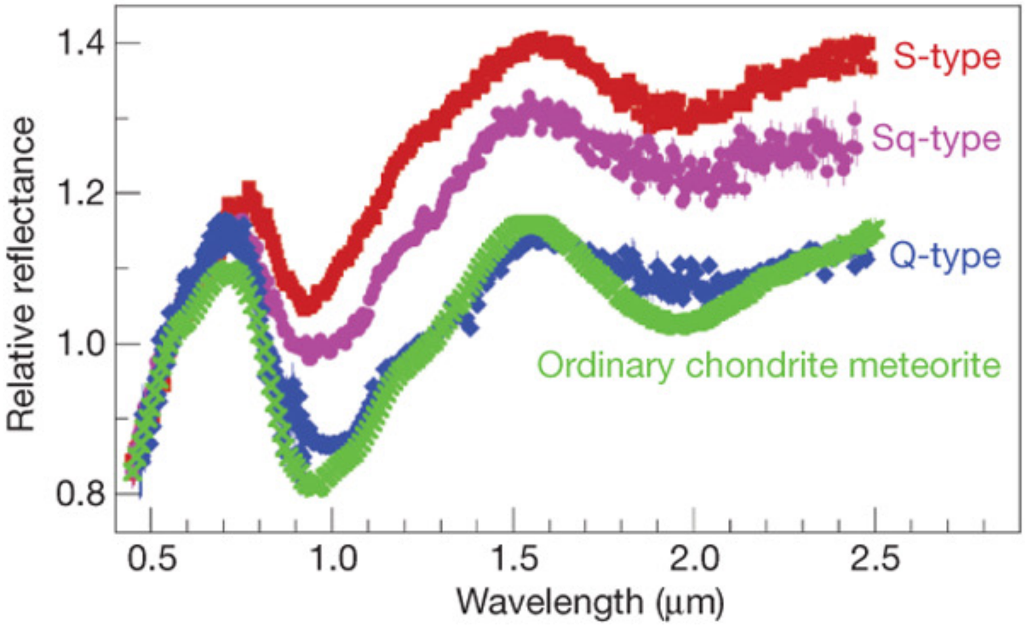
Direct observation of resurfacing due to tidal effects

What:

- Apophis may experience resurfacing during the encounter due to tidal effects
  - Available predictions of Apophis encounter (R_E ~ 6) vary from no motion to movement of meter-scale boulders.
  - Statistical assessment of the Near Earth Asteroid population implies that encounters within ~ 16 R_E causes substantial resurfacing.



Hirabayashi 2021



Direct observation of resurfacing due to tidal effects

How:

- Movement of surface material can be diagnosed by looking for shifting of material, changes in albedo, changes in spectral slope, and changes in spectral bands.
- Comparing high resolution, multi-band images taken **before and after** encounter will allow identification of surface alterations due to ***this*** encounter.
    - Imaging of regions predicted to be more prone to resurfacing **during** the encounter would provide additional details about the interaction
- A multi-band, optical-near ir, high resolution camera similar to those flown on other missions (e.g. Dawn) is appropriate for the investigation
- Images could be obtained from one spacecraft which rendezvous with Apophis prior to the encounter and remains there, or could be obtained from different spacecraft visiting before and after the encounter

Direct observation of resurfacing due to tidal effects

Why:

- Surfaces of asteroids are the result of a variety of geophysical processes
- Understanding these processes and their interplay is essential in order to connect the observable face of asteroids to their history
- Apophis' Earth encounter provides a rare opportunity to directly observe a geophysical process
    - Most of our understanding of geophysical processes on small bodies are acquired from "forensic" observations. This encounter provides unique opportunity for contemporaneous observations
    - Archeology vs. Anthropology
- A detection of resurfacing from tidal effects will enable detailed study of this process and estimates of regolith cohesion.
- A robust non-detection will enable limits on regolith cohesive strength and provide insight about the role of tidal interactions in resurfacing of asteroids.

Direct observation of resurfacing due to tidal effects

1. *Investigation must capitalize on the close encounter* ✓
    - Rare opportunity to directly observe a geophysical process, eliminating the uncertainties inherent in forensic investigations about time scales and causes
2. *Result of investigation must provide valuable information for either Planetary Science or Planetary Defense* ✓
    - Understanding the role and ubiquity of geophysical processes such as tidal resurfacing is necessary to connect the surface of asteroids to their history
    - Cohesive strength of regolith is an important factor in how asteroid surfaces respond to disturbances, whether natural or caused by humans
3. *Investigation must rely on mature, demonstrated technologies* ✓
    - Appropriate high-resolution, multi-band cameras have been flown on multiple missions
    - A variety of mission profiles (rendezvous, multiple fly-bys, …) are suitable
    - There are robust models capable of evaluating the observed (or not-observed) phenomenon

Leveraging spin change to investigate mass distribution and strength

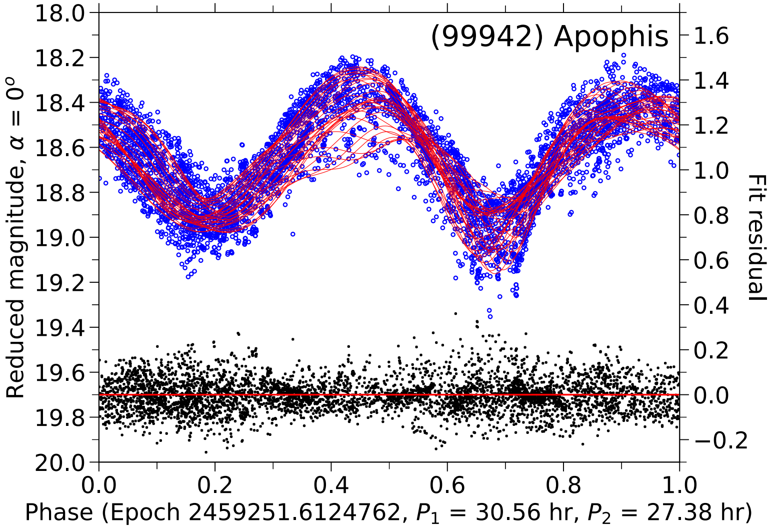
What:

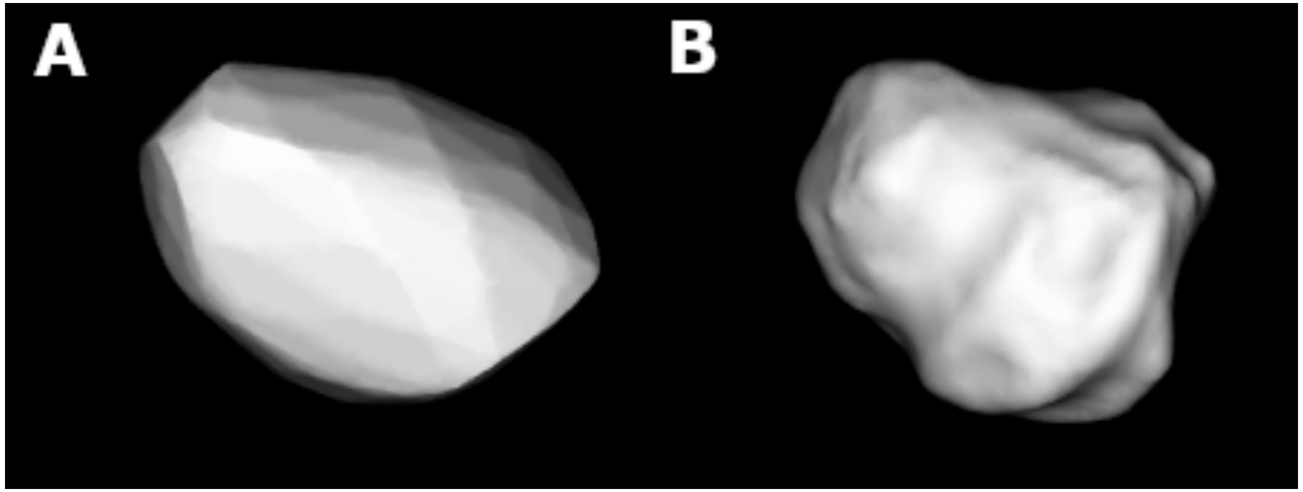
- Apophis is a Non-Principal Axis rotator
    - A comparison of the dynamical and shape-based moment of inertia ratios provide insight about mass distribution
- Apophis will most likely experience a change in spin state
    - Models of spin state change provide additional constraints about the uniformity of the internal mass distribution
- Comparisons of pre- and post- encounter moment of inertia ratios may provide insight about shape changes and the asteroid’s strength.

Leveraging spin change to investigate mass distribution and strength

How:

- Spin measurements pre- and post- encounter can be made using ground based optical photometry and radar
  - Spin measurements at each epoch yield dynamical moment of inertia ratios
- Radar can provide high resolution shape model pre- and post- encounter
  - Shape-based moment of inertia ratios can be derived assuming uniform density





Leveraging spin change to investigate mass distribution and strength

Why:

- The interior structure of an asteroid carries the imprint of it's collisional and accretion history, and is therefore a window into the evolution of the inner solar system.
- The interior structure of an asteroid is one of the major sources of uncertainty in how it would react during atmospheric entry or to a mitigation attempt.
- Interior structure has been probed for very few asteroids. Either an inhomogeneous or a homogenous mass distribution will provide insights about the structure of rubble pile asteroids.
    - Existing measurements of Apophis yield a homogeneity at the 5-10% level.
    - Limits at the ~1% level should be feasible from this investigation.
- A shape change, or lack there of could be leveraged to place constraints on the asteroid's strength.

Leveraging spin change to investigate mass distribution and strength

1. *Investigation must capitalize on the close encounter* ✓
   - Spin change due to the encounter enables this investigation
2. *Result of investigation must provide valuable information for either Planetary Science or Planetary Defense* ✓
   - Information about the interior structure of asteroids informs models of small body evolution as well as planetary defense atmospheric entry and mitigation models.
3. *Investigation must rely on mature, demonstrated technologies* ✓
   - Ground based radar and light curve photometry are robust technologies with active communities
   - Models of spin state changes due to Earth encounters have successfully been used to reduce uncertainty in the state of knowledge about asteroids.

Other intriguing, though not prioritized opportunities

- Electrostatic Lofting
  - As Apophis passes through the Earth’s magnetotail and outer Van Allen Belts, the change in environment could increase the effectiveness of electrostatic lofting – providing a unique experiment into the details of this process.
  - So far, there are no studies in the literature that assess electrostatic lofting during Apophis’ close approach.
- In situ seismometry
  - Tidal energy may be transmitted and dissipated as seismic waves and could provide unique insights about Apophis’ interior structure and strength.
  - Seismometry of low gravity bodies requires undemonstrated technology
- Ground based, long wavelength radar
  - Long wavelength radar may be able to probe the structure of the top tens of meters
  - Technique is not yet demonstrated

Additional Considerations

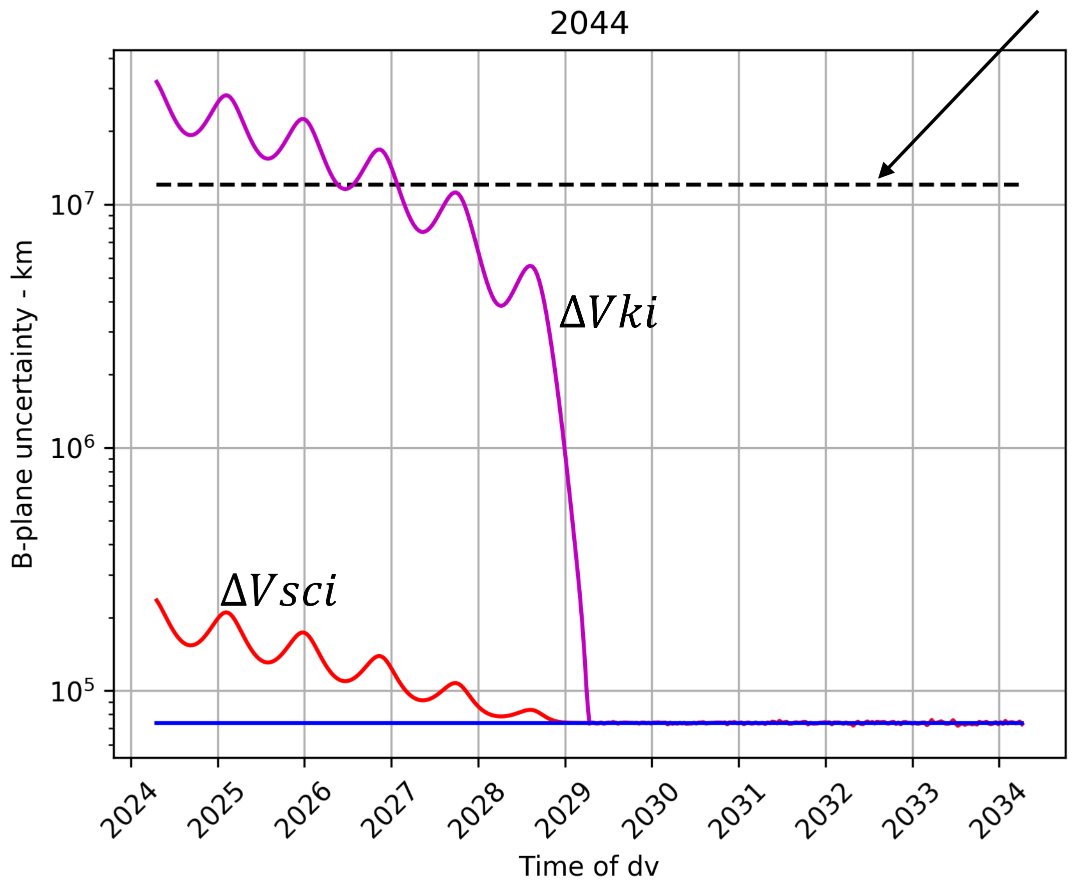
- Apophis encounter is an opportunity to demonstrate the utility of several observing methods which are not commonly used for small bodies research such as long wavelength radar, optical polarimetry, and speckle photometry.
- The overall science output from the encounter would benefit from practice campaigns, coordination, and timely data sharing.
- The design of spacecraft visiting Apophis near the close approach should include a plan for robust operations during radar observations.

Hazard Assessment

S. Chesley & D. Farnocchia

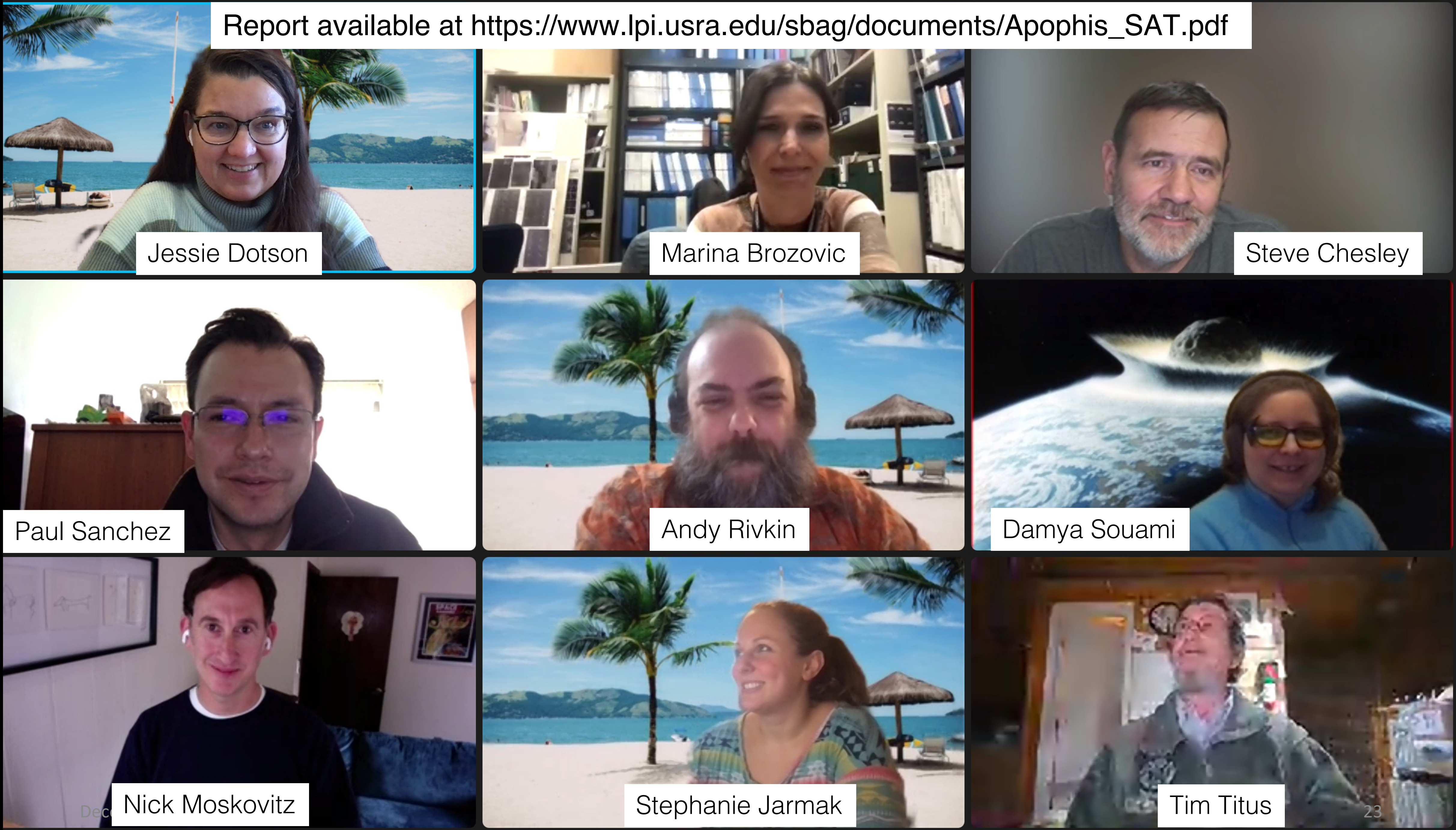
- Assessed effects on potential Earth impacts over the next century due to a spacecraft which interacts with Apophis anytime between April 2024 – April 2033
- Considered two representative values of ΔV
  - ΔVki = 1 mm/s; representative of a kinetic impactor mission
  - $\Delta Vsci$ = 7 μm/s; plausible upper limit for a science mission
- $\Delta Vsci$ does not result in an Earth impact over the next century
- ΔVki depends on when it is imparted on to Apophis
  - if applied prior to April 2029 ΔVki greatly increases the spread of possible trajectories after the 2029 encounter and thus require a detailed analysis
  - If applied after April 2029, ΔVki does not result in an Earth impact over the next century.

Hazard Assessment:
b-plane uncertainty at 2044 Earth encounter



Uncertainties below this line mean we know Apophis will miss Earth

Report available at https://www.lpi.usra.edu/sbag/documents/Apophis_SAT.pdf



Backup

Effects of the 2029 Earth Encounter on Apophis

ELSEVIER

Icarus
Volume 178, Issue 1, 1 November 2005, Pages 281-283

Note

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D.J. Scheeres [a], L.A.M. Ben

ELSEVIER

Icarus
Volume 242, 1 November 2014, Pages 82-96

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Yang Yu [a, b], Derek C. Richardson [b], Patrick

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Joseph V. DeMartini [a], Derek C.
B. Plescia [b], Petr Scheirich [c], Petr Pra

ELSEVIER

Icarus
Volume 365, 1 September 2021, 114493

Research Paper

Finite eleme
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M. Hirabayashi [a, b], Y. I

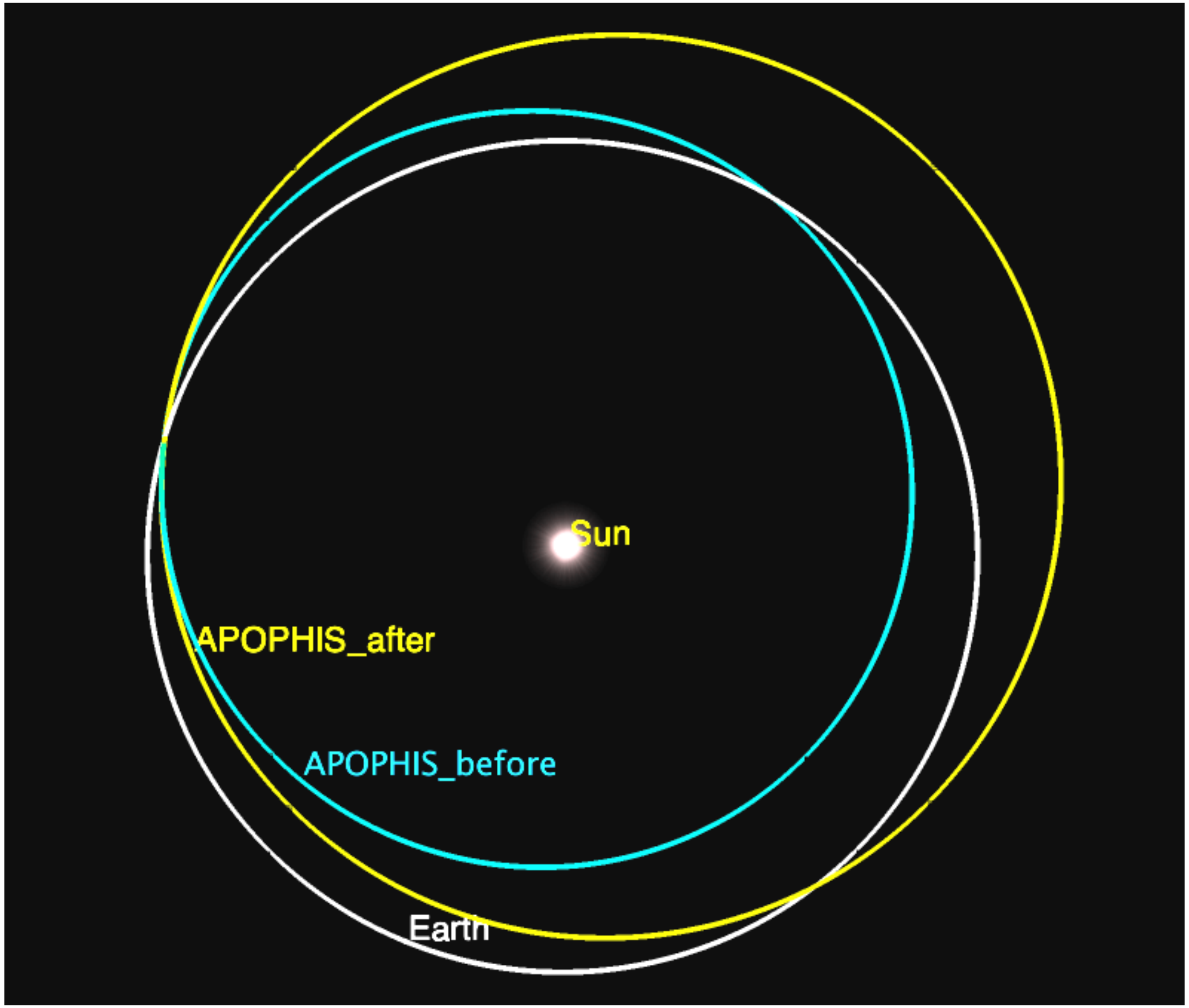
JOURNAL ARTICLE

APOPHIS – effects of the 2029 Earth's encounter on the surface and nearby dynamics

G Valvano, O C Winter, R Sfair, R Machado Oliveira, G Borderes-Motta, T S Moura

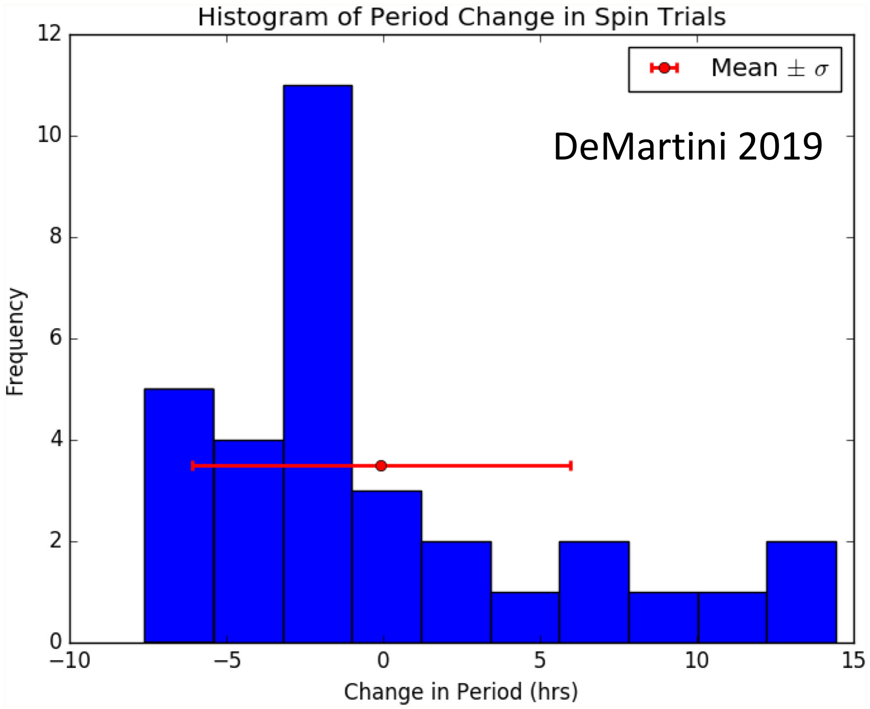
Monthly Notices of the Royal Astronomical Society, Volume 510, Issue 1, February 2022, Pages 95–109, https://doi.org/10.1093/mnras/stab3299
Published: 13 November 2021 **Article history** ▾

Apophis' Orbit will change from Aten to Apollo

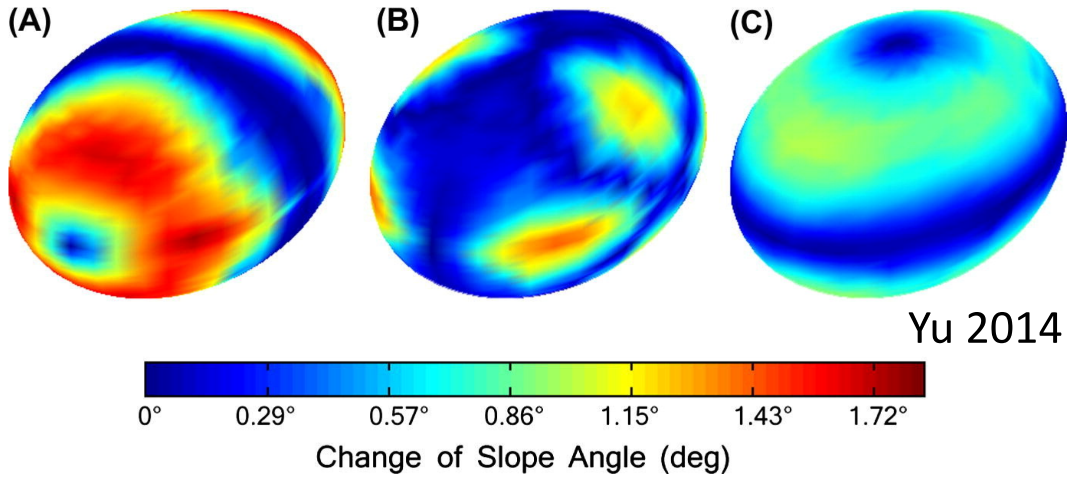


Apophis' spin will most likely change

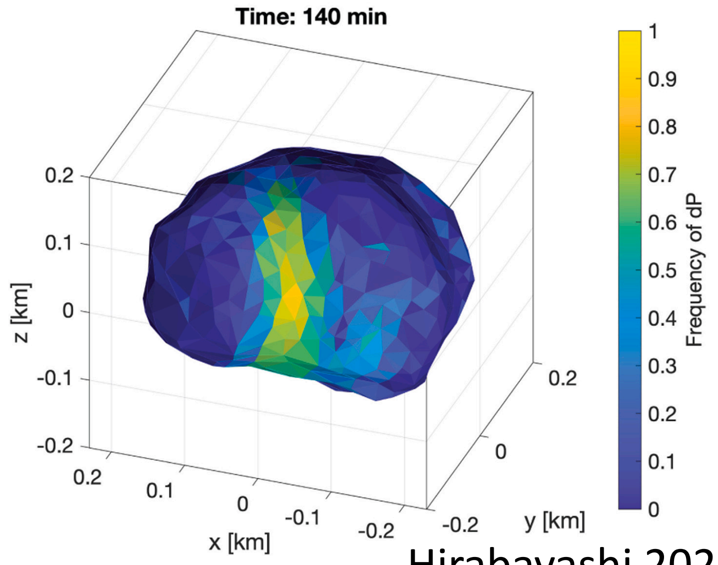
- Predictions in literature vary, though there is consensus that spin state is likely to change
- Change could be as large as several hours
  - Current spin state is known to a small fraction of an hour
- Major source of uncertainty is the orientation during Earth encounter



Apophis' surface may experience localized areas of resurfacing



Yu 2014



Hirabayashi 2021

- Predictions in literature vary, and depend on:
  - Asteroid shape
  - Regolith properties
  - Modeling approach
  - Assumed density
- Trend is to predict a possibility of localized resurfacing in areas of higher slope

Apophis' might experience small changes in shape

- Details of predictions in literature vary, though current trend is to expect very small, if any, changes in shape

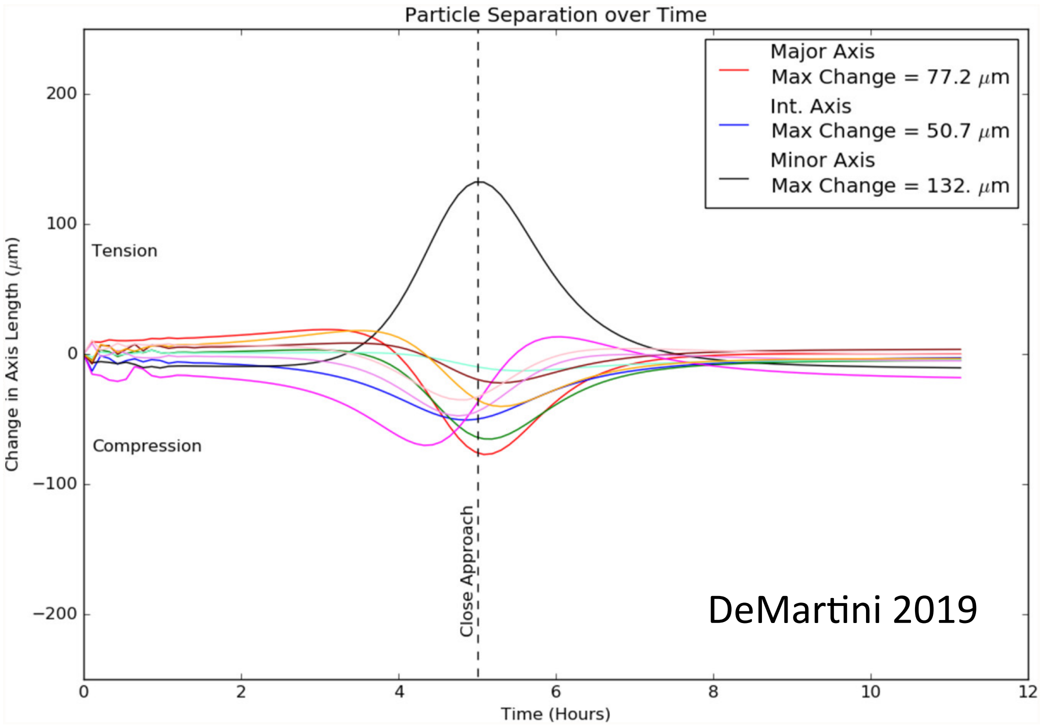


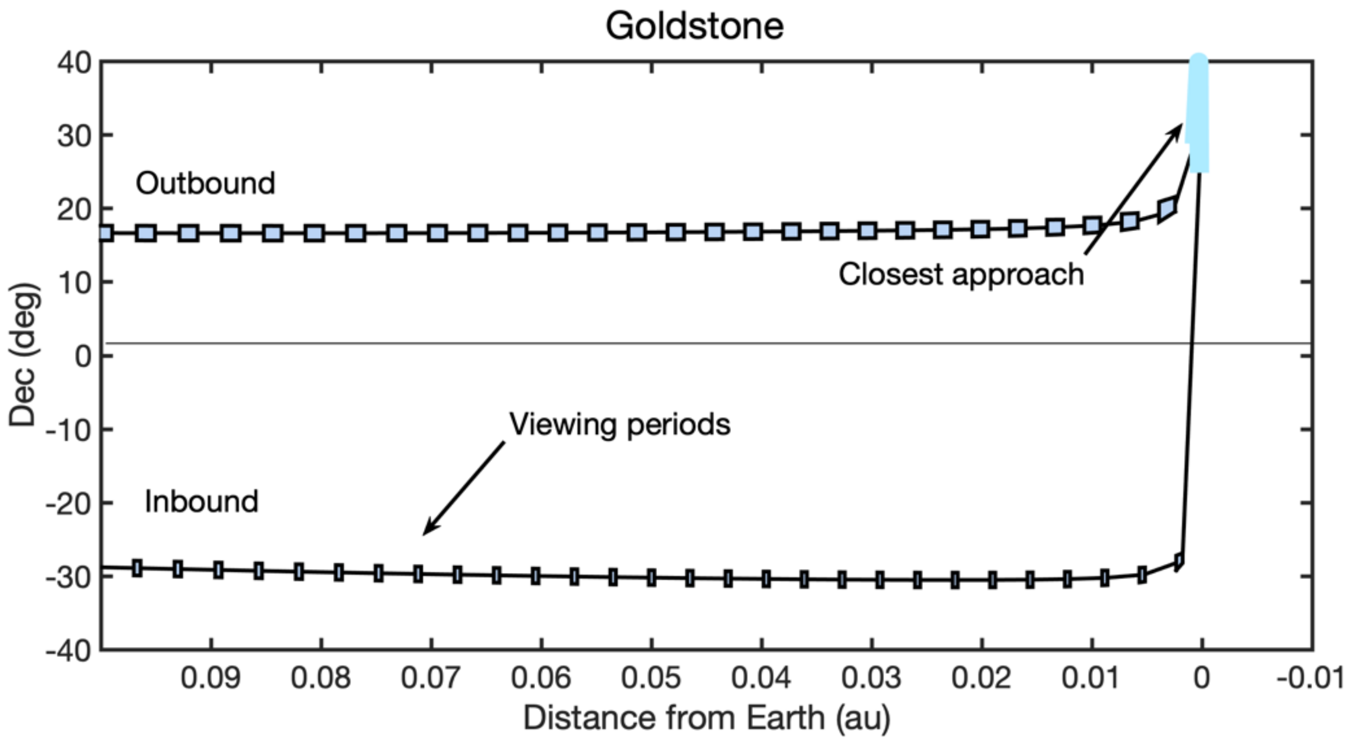
Table 1. Apophis science in 2029 enabled by ground-based radar facilities

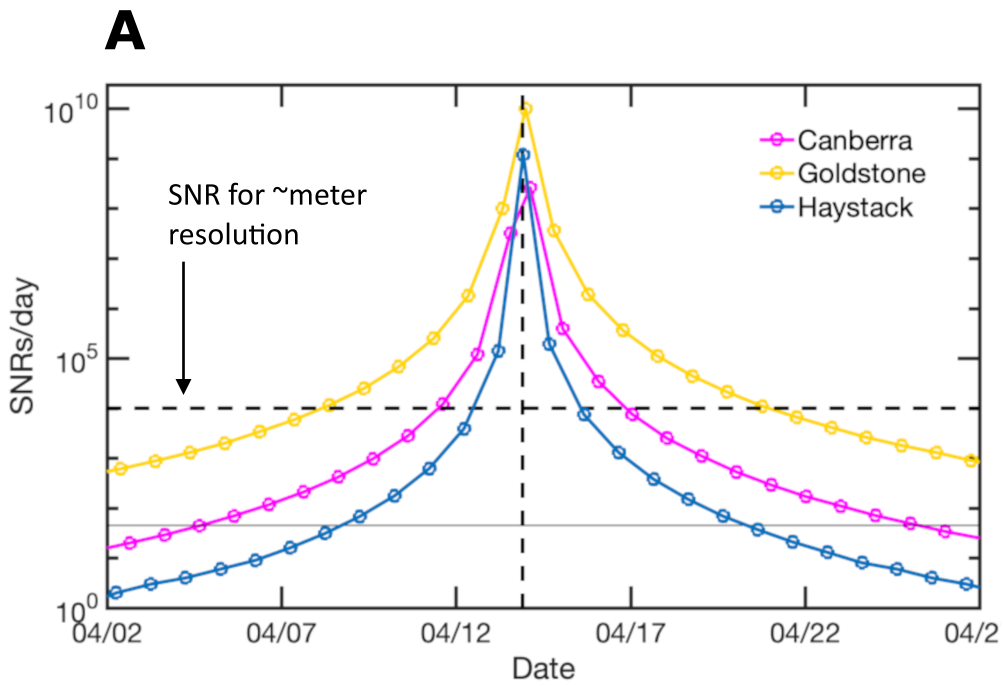
Radar frequency	Immediate data products	Apophis science	Example Facilities	Current facility usage
>10 GHz	• cm-to-decimeter range resolution SURFACE imaging; • radar astrometry; • radar scattering properties and polarimetry	• super-small scale surface geology; • 3D-shape model reconstruction; • spin state; • moment of inertia ratios; • heliocentric orbit improvement; • cm-scale surface changes; near-surface roughness and bulk density; • radar albedo; • regolith deposits	HUSIR (Lincoln Labs)	Observations of space debris, LEO, and GEO targets; Observed one NEA to date (2012 DA14)
7–9 GHz	• 1.875 m and coarser range resolution SURFACE imaging; • radar astrometry; • radar scattering properties and polarimetry	• surface features and surface geology; • 3D-shape model reconstruction; • spin state; • moment of inertia ratios; • heliocentric orbit improvement; • meter-scale surface changes; • near-surface roughness and bulk density; • radar albedo; • regolith deposits.	Goldstone DSS-14 and DSS-13; Canberra DSS-43	Spacecraft communication; NEA observations are frequent and routine
10-500 MHz	• decimeter to tens of meters range resolution INTERIOR imaging; • radar scattering properties	• internal structure constraints: degree of homogeneity & porosity; • radar albedo	MISA, CMOR, OVRO, UNM–LWA, HAARP, ALTAIR, EISCAT 3D	Observations of Earth's atmosphere; • Observations of space debris, LEO, and GEO targets; • Proof-of concept stage for observations of NEAs

Table 2. Apophis science in 2029 enabled by ground-based and space-based optical facilities

Optical wavelength	Immediate data products	Apophis science	Example Facilities
IR	unresolved images	• effective diameter; • thermal inertia • limited mineralogy	NEO Surveyor
	spectra	• mineralogy and bulk composition; • space weathering; • taxonomy; • inferred microscopic surface density	SpeX@NASA IRTF
mm to sub-mm	unresolved? images	• thermal inertia	ALMA
Visible	lightcurves	• 3D convex shape model; • spin state; • moment of inertia ratios;	
	spectra	• taxonomy; • compositional analogs	ubiquitous
	occultation chords	• size; • limited shape information; • heliocentric orbit improvement	
	adaptive optics	• 10-m resolution images	SPHERE@VLT
	speckle imaging	• 10-m resolution images	QWSSI@LDT
	polarimetry	• regolith properties;• optical albedo;• surface heterogeneity	WIRC+Pol@Palomar 200"

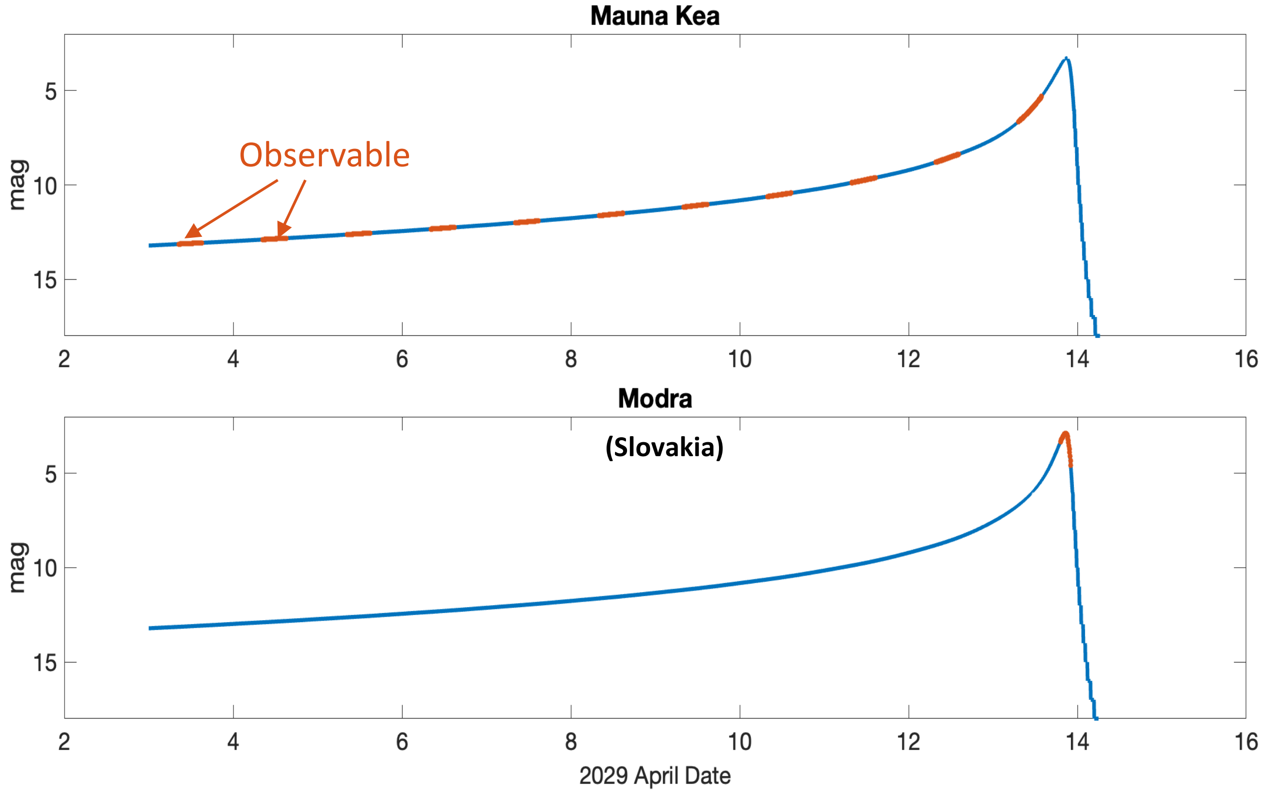
Close Approach Ground Observability - Radar

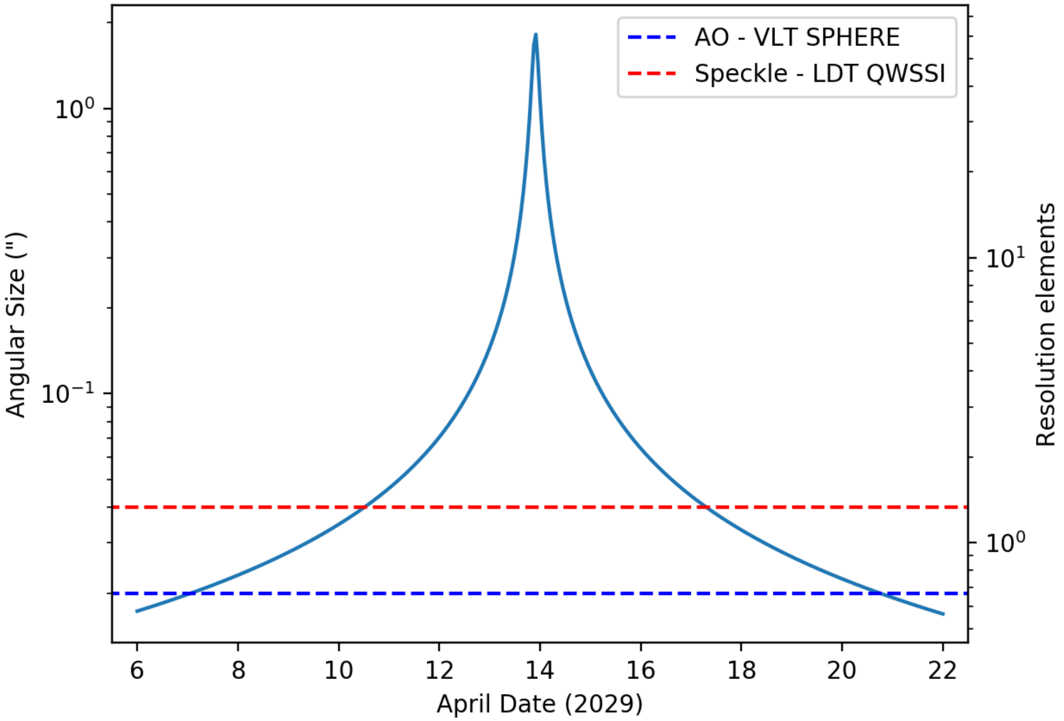




- Apophis is observable by radar from ~ mid-March through mid-May
- For several days surrounding close approach, the SNR will be sufficient for ~ meter scale resolution with existing facilities

Close Approach Ground Observability - Optical





- Prior to close approach, Apophis is observable from the southern hemisphere.
- At close approach, Apophis is observable from Europe
- Immediately after close approach, Apophis becomes a day time object.
- Angular size during close approach is suitable for high resolution imaging from ground